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Integrated Alternative Energy Systems for Use in Small Communities

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PREFACE

This paper summarizes the principles and conceptual design of an integrated alternative energy system for use in typical farming communities in developing countries. A system is described that, utilizing the sun and methane produced from crop waste, would supply sufficient electric and thermal energy to meet the basic needs of villagers for water pumping, lighting, and cooking. The system is sized to supply enough pumping capacity to irrigate 101 ha (249 acres) sufficiently to optimize annual crop yields for the community. Three economic scenarios were developed, showing net benefits to the community of \$3,578 to \$15,547 annually, payback periods of 9.5 to 20 years, and benefit-to-cost ratios of 1.1 to 1.9.

This paper was presented at the Seminar on Solar Energy Applications for Buildings, held November 17-19, 1980 in Mexico City. The seminar was a joint effort between the United States and Mexico. Solar Energy Research Institute (SERI) staff coordinated the seminar for the U.S. Department of Energy.

I. H. Usmani, Senior Energy Adviser to the Center for Natural Resources, Energy, and Transport at the United Nations, provided the original direction and funding from which this work resulted. Dr. James Gaddy of the University of Arkansas supplied the data on the effects of irrigation on crop yield and on the technical design and cost of the biogas system. Appreciation is also extended to James Gresham, formerly with the Industrial Applications and Policy Branch of SERI and now with Science Applications, Inc., for the economic analysis presented in this paper.

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SECTION 1.0

INTRODUCTION

According to United Nations estimates, one billion people live in remote areas of Asia, Africa, and Central and South America. The standard of living for these people is low; in many cases, barely enough for survival. Food and fuel supplies are insufficient. Electric power is generally unavailable to most villages; when present, it is usually supplied by a diesel engine (Fig. 1-1). Wood, dung, kerosene, and a variety of miscellaneous fuels are used for cooking and heating. Families may spend 20% or more of their annual incomes on cooking fuel. Most needs of these remote communities can be satisfied by alternative energy systems.

Some communities have been supplied with a single alternative technology, such as photovoltaics, as the energy source. These systems rely on a single resource and are highly susceptible to interruptions. During the last ten years, a concept has emerged that shows great promise in overcoming the limitations of single-technology systems. This concept integrates individual technologies, forming a centralized system that optimizes the use of resources while obtaining low overall energy costs and high annual availability.

Studies indicate that integrated systems are useful over a wide range of applications. For utility applications, the integration of wind or solar thermal plants with conventional power plants (particularly those using oil, natural gas, or hydropower) appears practical [1,2,3,4]. The solar plants, operating with or without storage, would function whenever sunlight or wind were available, thereby saving fuel oil, natural gas, or water.

Integrated systems designed specifically for use in small, isolated communities are being developed under the direction of the United Nations Development Program (UNDP). Projects either are underway or being considered in Sri Lanka, Mexico, Pakistan, and Senegal [5,6,7]. SERI staff have participated in two of the UNDP studies: in 1978 for Mexico, and in 1979 for Pakistan [8,9].

Figure 1-1. Kelly and Lewis 22 hp Diesel Engine
Small diesels are the current mainstays for remote pumping and electrical generation in developing countries.

SECTION 2.0

FUNDAMENTALS OF INTEGRATED SYSTEMS

Figure 2-1 illustrates the basic concept of the integrated system for rural and small community applications. Although this example assumes that wind, biomass, and solar systems operate together, nearly any combination of alternative technologies is possible—including low-head hydroelectric. The choice of technologies depends upon available resources at the site.

In the community represented by Fig. 2-1, electricity is supplied by photovoltaics, wind turbines, and biogas-fired generators to handle domestic loads (e.g., lighting) and agricultural loads (e.g., pumping water). Water pumped to irrigate land is sufficient to produce two crops annually. Anaerobic digestion of crop waste resulting from the controlled irrigation produces biogas for cooking and for fueling the generator, which in turn supplies electricity and shaft power. Because crop waste and the resulting gas can be stored, the biogas-fired generator can act as an intermediate load plant, thereby minimizing the amount of battery storage necessary to efficiently utilize the energy from the photovoltaic panels and wind turbines. Residue from the reactors is returned to the fields with little (if any) loss in fertilizer value as a result of the anaerobic digestion process.

An additional benefit is that the integrated system is a community project (i.e., a village utility), operated and maintained by a small force recruited from the local population. Steady employment and training probably will result in higher quality maintenance than is attainable with family-owned systems.

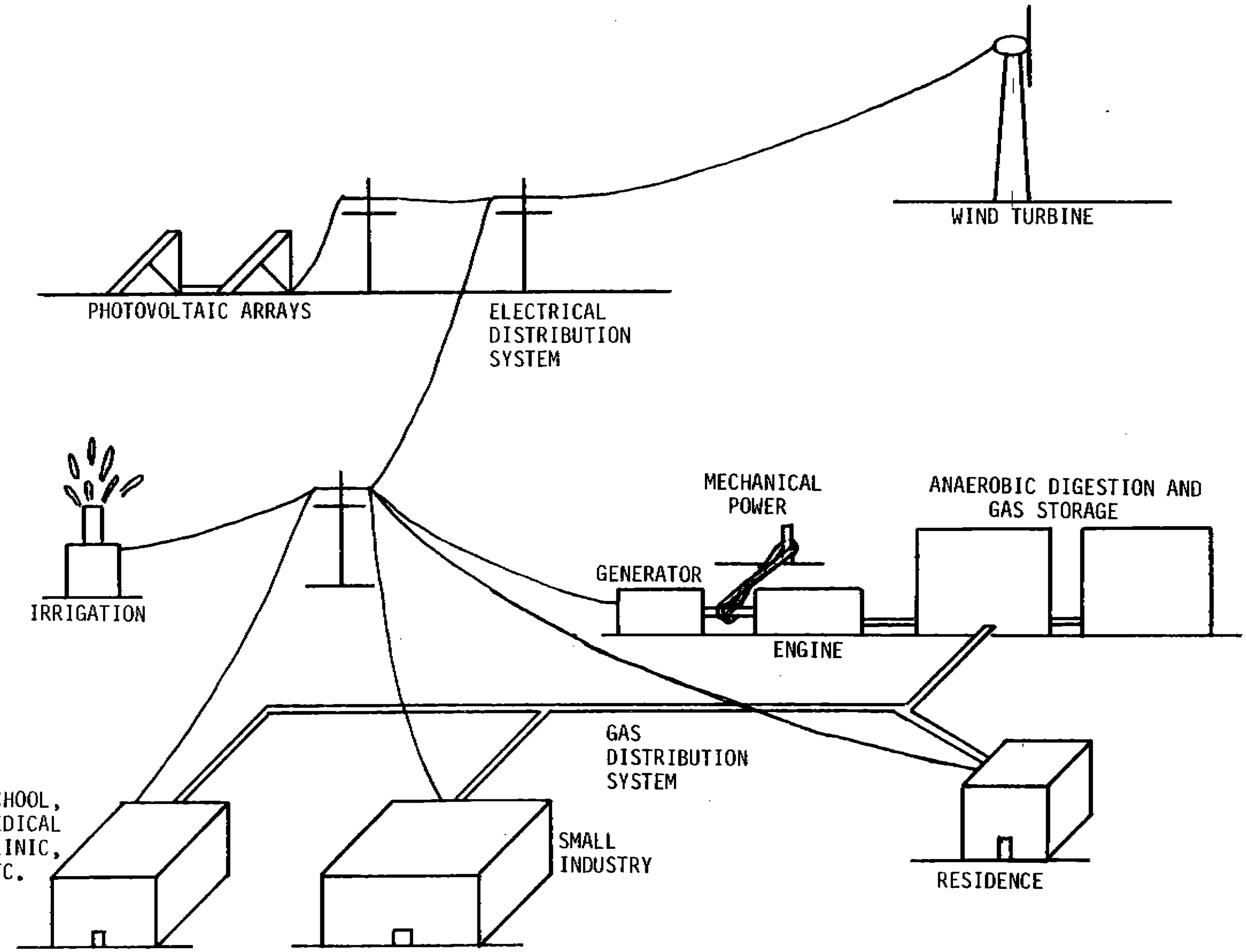

Figure 2-1. Pictorial Diagram of a Typical Integrated System, Showing Applications

SECTION 3.0

DESIGN OF A TYPICAL INTEGRATED SYSTEM

The characteristics of a typical farming community in a developing country are listed in Table 3-1. The minimum amounts of energy and water required annually by such a community (as estimated by the United Nations) are shown in Table 3-2 [5]. Figure 3-1 shows the annual energy requirements for this community, categorized by energy form. Most of the required energy (84%) is thermal and is used for cooking; the remainder (16%) is electrical and is used to provide community power and irrigation pumping. Crop irrigation accounts for nearly 90% of all electricity used (see Fig. 3-2).

When the energy application is located near the energy source, mechanical (shaft) power may be the most efficient and economical approach and should not be ignored during the initial selection of technologies.

A conceptual design of an integrated system is presented for the community described in Table 3-1. This community represents a specific site evaluated during a SERI study [9]. Rainfall supplies minimum irrigation for crop production and grazing. The annual demand of this community, according to standards supplied by the United Nations[5], is 1845×10^6 kJ (1750×10^6 Btu) of thermal energy and 98,935 kWh of electrical energy (Table 3-3). The design satisfies 100% of village fuel and electrical requirements and provides supplemental irrigation to optimize production from 101 ha (249 acres), or approximately 45% of the cultivated land available to the community.

The integrated system is sized to provide sufficient crop waste [4.4×10^5 kg (492 t)] to generate gas for 100% of the village thermal and electrical needs and 80% of the electrical needs for irrigation. The photovoltaic array supplies the remaining 20% of the electrical energy needed for enough irrigation to grow one crop each of corn and wheat. Technically, the total capacity of the system could be increased to irrigate 100% of the available land, producing more grain and crop waste. Capital cost, however, would increase and could become excessive.

The flow of resources and a schematic diagram for the system are illustrated in Figs. 3-3 and 3-4, respectively. The 11 wells, community center, and flour mill are scattered over a wide area. The wind resource at this site is minimal; however, insolation is plentiful. The system utilizes photovoltaics and anaerobic digestion of crop waste to obtain both electrical and thermal energy. The energy generated by each subsystem is shown in Table 3-4. All of the thermal and most of the electrical energy (80%) is obtained from the biogas subsystem, which acts as a baseload plant. The photovoltaics subsystem supplies electrical energy when possible.

Biogas is stored at relatively low pressures; the storage capacity is sized to provide a constant supply for cooking and for operation of the engine-generator. Crop waste is stored as it becomes available, and is fed throughout the year to the digesters.

The rated capacity of the engine-generator is 30 kW_e. The internal combustion engine will be modified to use biogas with an approximate methane content of 50%. Engine performance must be derated for this application and is approximately 60% of normal at full load. The estimated lifetime of this engine is 10 years. A small amount of battery storage is used to smooth transients and provide backup when the engine-generator is unavailable. This electrical storage is sized to provide a one-day supply of electricity for all loads except irrigation.

Table 3-1. **CHARACTERISTICS OF A SAMPLE RURAL COMMUNITY IN A DEVELOPING COUNTRY**

Population	700
Number of wells	11
Lift of water [m (ft)]	20 (66)
Land available for cultivation [ha (acres)]	223 (550)
Number of dwellings	70
Livestock	530

Table 3-2. **AVERAGE ANNUAL ENERGY AND WATER REQUIREMENTS FOR A TYPICAL RURAL COMMUNITY [5,9]**

Function	Requirements
Cooking	2.6×10^6 kJ (2.5×10^6 Btu)/person/yr
Lighting	
Homes	150 Wh/home/night, as follows: one 15-W lamp for 5 h/night one 15-W lamp for 3 h/night one 15-W lamp for 2 h/night
Street	250 Wh/pole/night (25 W for 10 h/night/8 houses)
Water	
Human	10 L (5.3 gal)/person/day
Stock	20 L (10.6 gal)/animal/day

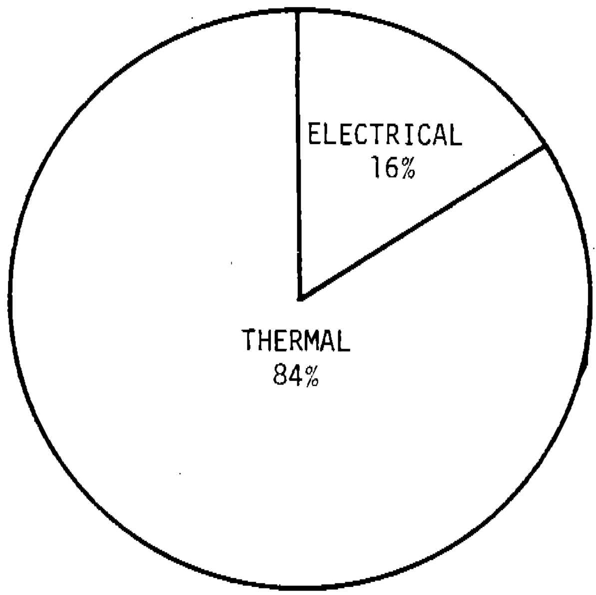

Figure 3-1. Breakdown of Energy Usage for the Sample Rural Community

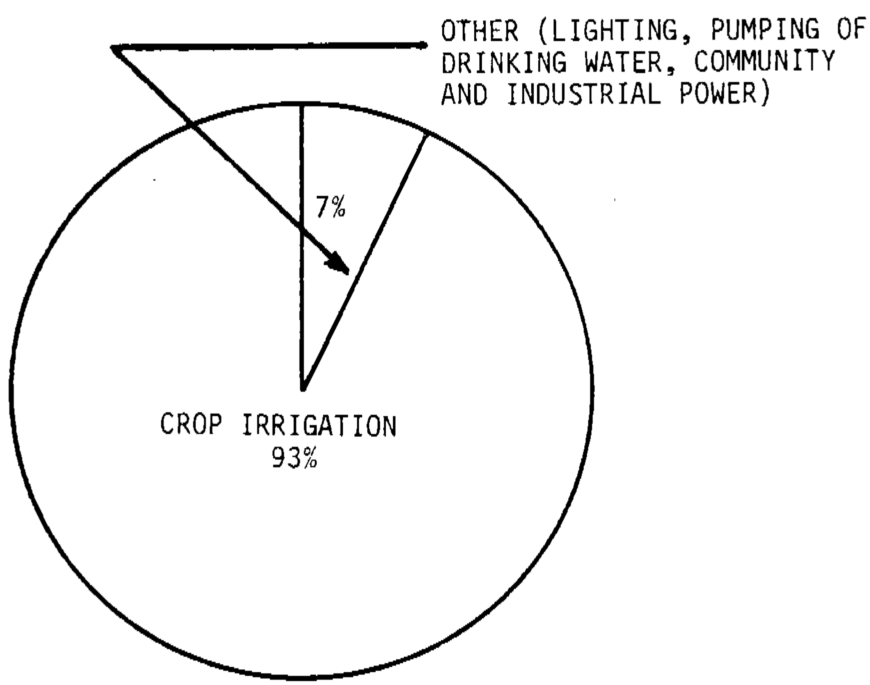

Figure 3-2. Breakdown of Electrical Energy Usage by Application for the Sample Rural Community

Table 3-3. ANNUAL ENERGY DEMAND OF A SAMPLE RURAL COMMUNITY

Energy Form	Application	Annual Energy Required[a]	Percentage of Demand Provided
Thermal	Cooking	1846×10^6 kJ (1750×10^6 Btu)	100
Electrical	Lighting		
	House	3,833 kWh	100
	Community	822 kWh	100
	Water pumping		
	Human	634 kWh	100
	Stock	700 kWh	100
	Crop irrigation	92,033 kWh	45
	Community uses[b]	913 kWh	100

[a]Includes losses for distribution of energy.

[b]Energy for schools, medical clinic, etc.

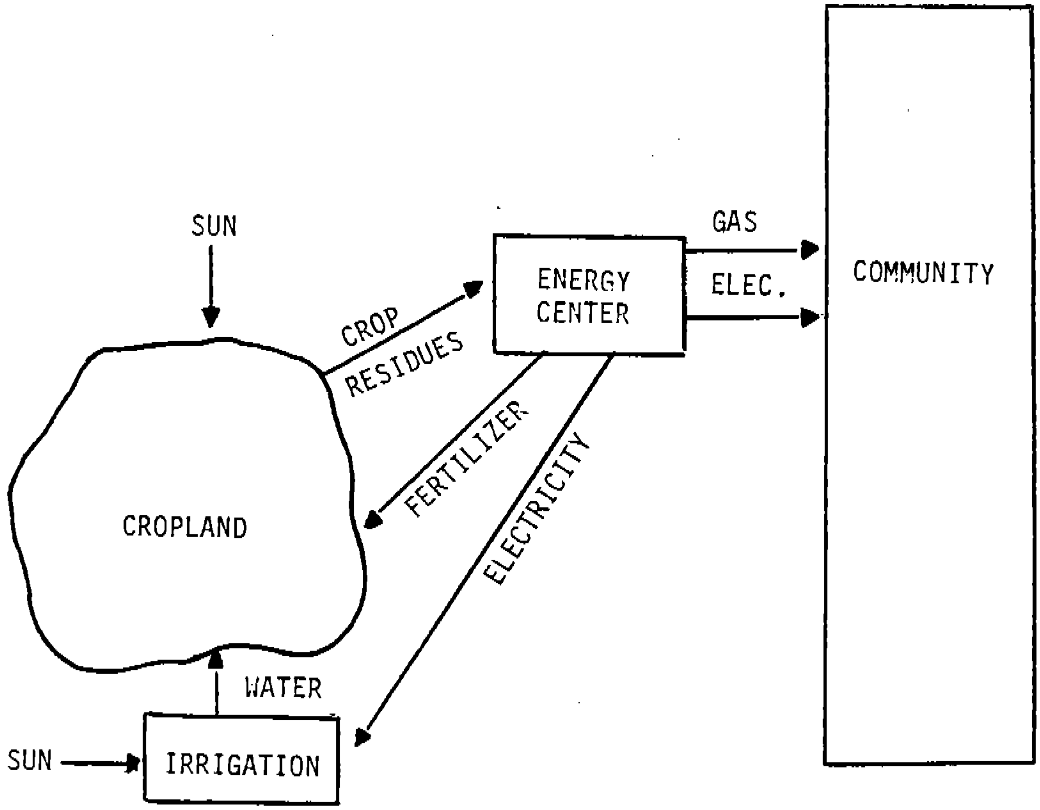

Figure 3-3. Flow of Resources for the Integrated System

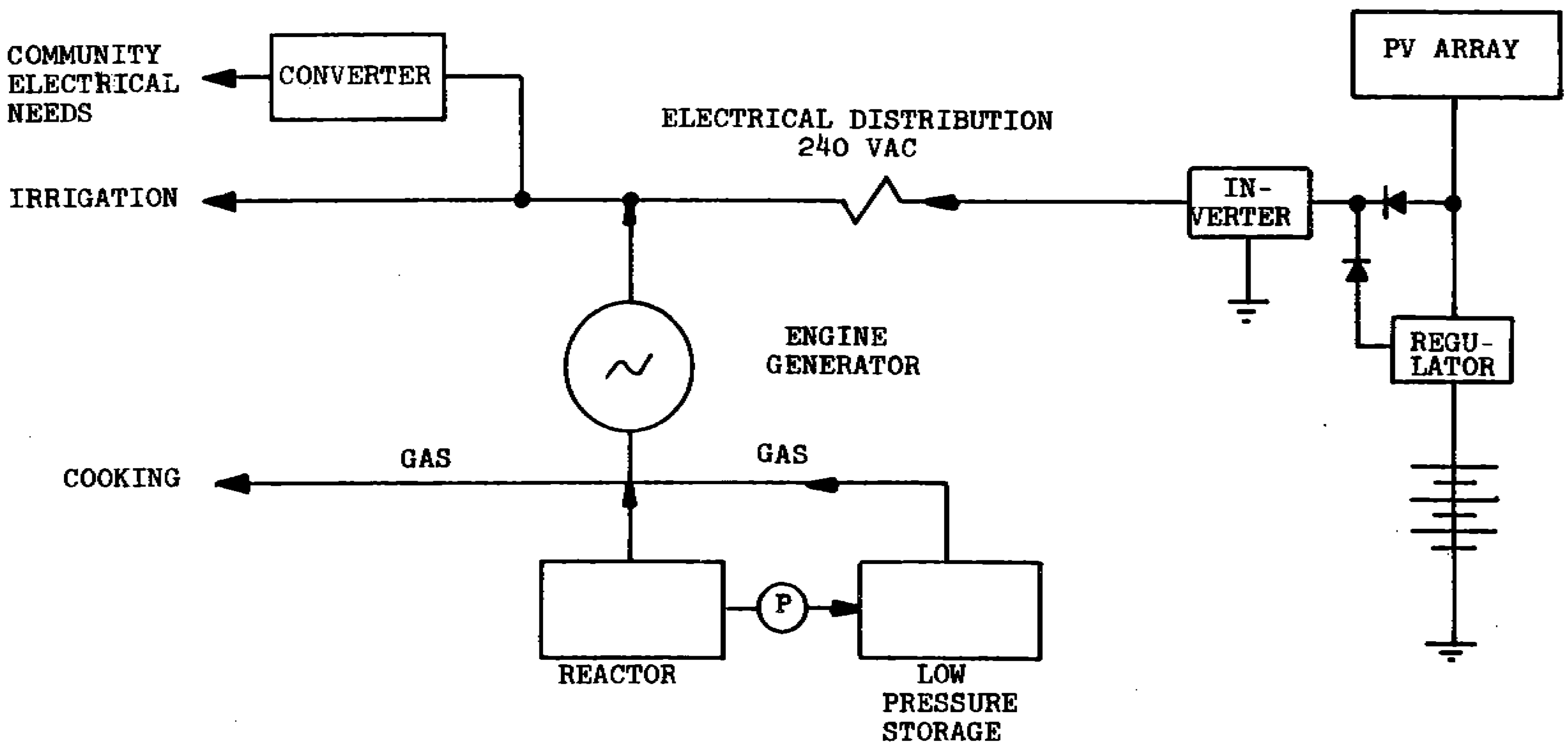

Figure 3-4. Simplified Schematic Diagram of Integrated System

Table 3-4. ENERGY SUPPLIED TO COMMUNITY BY TECHNOLOGY

Energy Form	Source	Annual Energy Supplied[a]
Thermal	Biomass	1846×10^6 kJ (1750×10^6 Btu)
Electrical	Biomass	80,000 kWh
Photovoltaic		19,640 kWh
	TOTAL	99,640 kWh

[a]Includes distribution and storage losses.

The photovoltaic panels are of a conventional type manufactured in the U.S. today. They are nonconcentrating and nontracking to minimize operation and maintenance costs and to increase reliability. The rated capacity of the photovoltaic subsystem is 12.3 kW_e.*

Elevated tanks are used to store drinking water for humans. Reservoirs hold drinking water for stock and water for irrigation and are used as needed.

The full-system specifications are too lengthy to describe in this paper. However, key efficiencies assumed were electrical transmission, 90%; pumping, 65%; field application, 67%; and storage, 80%. System components were sized accordingly. Crop yields and irrigation requirements were obtained from Ref. 11.

Table 3-5 shows the estimated effects of irrigation. Regular, supplemental irrigation of the cropland produces four to eight times the yield obtained from unirrigated land that is dependent upon rainfall alone [11]. In addition, two crops can be grown each year instead of the customary one. The annual two-crop yield from the 101 ha (249 acres) is corn, 3.0×10^5 kg (329 t); wheat, 2.5×10^5 kg (274 t); and crop waste, 6.3×10^5 kg (691 t).

In this village, bullocks (plow animals) are fed from approximately 1792 kg/ha (0.8 t/acre) of crop waste traditionally reserved for them. Supplemental irrigation therefore makes crop waste of 4.5×10^5 kg (492 t) available annually for the digester to generate biogas. Residue from the digestion process totals 1.0×10^5 kg (108 t) and is returned to the soil as a conditioner.

*Based upon 1.6 $kWh/W_p/yr$, an assumption requested by the United Nations. This assumption is reasonable when compared to actual panel performance. Solarex tests their panels as having annual energy output up to 1.6 kWh/W_p for "average U.S. insolation" [12]. Spectrolab Block II modules mounted in fixed east-west positions are quoted as having annual outputs of 1.5 to 2.4 kWh/W_p, depending upon the location [13].

Table 3-5. ESTIMATED EFFECTS OF IRRIGATION [11]

Total irrigated land, ha (acres)	101 (249)
Annual crop yield, kg (t) per 101 ha (249 acres)	
Corn	3.0×10^5 (329)
Wheat	2.5×10^5 (274)
Waste yield, kg (t)[a]	4.5×10^5 (492)
Reactor residue, kg (t)[b]	1.0×10^5 (108)

[a]Net yield after 1792 kg/ha (0.8 t/acre) have been subtracted for use as cattle feed.

[b]Usable as soil conditioner.

SECTION 4.0

ECONOMICS OF THE INTEGRATED COMMUNITY SYSTEM

Capital costs of the integrated system and its components are shown in Table 4-1. Estimated lifetimes are given for each major component or subsystem. Costs for the biogas system and engine-generator were obtained from Ref. 11. The solar cell module cost is based upon 1982 production estimates by ARCO Solar, Inc. [14]. The remainder of the system capital cost is the result of studies performed at SERI.

Operation and maintenance costs of the biogas subsystem have been estimated at 9% of the installed capital cost per year [11] and include labor for collecting the crop waste and removing and distributing the residue from the reactors. Operation and maintenance costs for the balance of the integrated system have been estimated to be 4% of the installed capital cost annually. In addition, certain major components need periodic replacement (Table 4-1). Replacement costs have been assumed at appropriate times in the 30-year plant life.

Table 4-2 presents three possible economic scenarios for the integrated system. All three assume a crop value of \$0.15/kg (\$140/t) for wheat, \$0.18/kg (\$160/t) for corn, and no value for the residue as a fertilizer or soil conditioner. The three scenarios also assume loan interest rates similar to those available now to developing countries.

Scenario One assumes that photovoltaic modules are available at \$5/W_p, that there is a loan interest of 5%, and that there is no escalation in value of both energy and crops over the 30-year lifetime of the plant. The values of kerosene and electricity displaced by the integrated system are representative of those in countries where heavy government subsidies occur.

Using these data, the annual net benefit* to the community (the net value of the grain produced and fuel saved, after all operating expenses are paid) is \$15,547 annually, resulting in a payback period of approximately 11 years. The benefit-to-cost ratio* is 1.4.

If all conditions are held constant for Scenario Two—with the exception of the interest rate, which is increased to 10%—the net benefit drops to \$3,578 annually. The payback period is increased to 20 years and the benefit-to-cost ratio is 1.1.

These first two scenarios are extremely conservative, both in their assumption of the costs of electricity and kerosene and in their assumption of no escalation in these energy sources. No value has been assigned to the residue from the digestive process or its effect on crop production. Scenario Three describes a more realistic situation in which the prices of kerosene and electricity are \$0.26/L (\$1.00/gal) and \$0.075/kWh and where these costs are expected to escalate at 5% annually. The interest on the loan remains at 10%. Economic benefits are greatly improved. The levelized annual benefit to the community is \$28,385. The payback period is reduced to 9.5 years while the benefit-to-cost ratio increases to 1.9. This last case still does not credit the 1×10^5 kg (108 t) of reactor residue produced annually with any value as a fertilizer. Although the impact of such residue on crop production is not definitely known and its market value will vary from country to country, its use will enhance the economics of the integrated system.

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*The annual net benefit and benefit-to-cost ratios are defined in Table 4-2.

Table 4-1. ESTIMATED PRESENT DAY CAPITAL COST OF INTEGRATED SYSTEM[a]

Item	Cost (1980$)	Assumed Lifetime (yr)
Biogas generation	140,000[b]	30
Electrical generation	19,000	10
Photovoltaic subsystem	73,800[c]	30
Electrical storage	3,820[d]	10
Pumps and motors	15,000	15
Balance of plant	40,100	30
System	291,720[e]	30

[a]Includes installation but excludes training, design, contingencies, etc.

[b]Estimate provided for local labor and some imported equipment.

[c]Includes PV modules at $\$5/W_p$.

[d]Includes power conditioning and water storage tanks.

[e]Capital cost does not include replacement costs at end of component life. These replacement costs are considered in yearly operations and maintenance cost.

Table 4-2. THREE ECONOMIC SCENARIOS FOR AN INTEGRATED SYSTEM

Scenario	Loan Interest (%)	Value of Energy		Escalation (%/yr)		Net Benefit to Community ($/yr)[a,b]	Payback Period (yr)	Benefit-to-Cost Ratio[c]
		Kerosene [$/L ($/gal)]	Electricity (¢/kWh)	Energy	Crops			
1	5	0.13 (0.50)	2.9	0	0	15,547	11	1.4
2	10	0.13 (0.50)	2.9	0	0	3,578	20	1.1
3	10	0.26 (1.00)	7.5[d]	5	0	28,385	9.5	1.9

[a]Based on net crop value of $76/ha ($188/acre).

bNet annual benefit = Annualized Energy Benefit + Annualized Crop Benefits-Annualized Loan Repayments - Annualized O&M Costs.

[c]Benefit-to-Cost Ratio (B/C) = (Annualized Energy Benefits + Annualized Crop Benefits)/Annualized Loan Repayments + Annualized O&M Costs.

[d]Based on World Bank Data.

Although the three economic assumptions are generally conservative and probably undervalue the effect of the integrated system, they show the considerable promise of these systems.

Similar economic analyses can be performed with any combination of alternative technologies, including hydropower. The results will vary significantly, depending upon the value of the energy produced and on other by-products such as grain or crop waste. The economics will improve as individual technologies (e.g., photovoltaics) become more cost-effective.

SECTION 5.0

TECHNICAL AND INSTITUTIONAL ISSUES

This paper presents relevant data on the technical and economic applicability of integrated systems to the energy problems of a country. In reality, the technical design of the system is inseparable from the social and cultural aspects of the community. A variety of technical and institutional issues must be addressed to ensure that maximum benefits are obtained [15].

Of the technical issues, one of the most important is the availability of water for irrigation. Hydrology for a given site must be thoroughly evaluated to guarantee that pumping at required rates can be sustained on a continuing basis.

Availability of resources such as insolation, wind, and hydropower needs careful assessment. Knowledge of the hour-by-hour distribution of resources will allow design of the most cost-effective system.

Crop yields vary widely with location, type of crops grown, and irrigation and fertilization patterns. Because crop values have a major effect on the economics, they must be carefully determined.

The design of the biogas system described in this paper is derived from Ref. 11. Questions remain, however, about conversion efficiency of crop waste to gas, the degree of attention required to maintain the digestive process, and the value of the residue as fertilizer. Ongoing research should soon provide some resolutions.

When estimating the benefits of a system, care must be taken not to upset the community structure more than necessary. In the case discussed in Sec. 3.0, it was assumed that bullocks, which are fed with crop wastes, would continue to plow the land; therefore, 1792 kg/ha (0.8 t/acre) of waste were subtracted from the yield available for digestion. Appropriate amounts of feedstock must be reserved unless sufficient farm equipment (and fuel) can be committed to replace the bullocks.

The question of funding and ownership is a serious one. In most countries, communities lack the capital to purchase an integrated system. Funds, along with reasonable interest rates, could be made available to the community either from a central government or from an appropriate agency such as the World Bank or United Nations.

SECTION 6.0

CONCLUSIONS

Integrated systems offer great potential for helping to offset world reliance on oil and natural gas. In the process of solving its energy problems, a community using integrated energy systems can greatly increase food production and achieve a high level of independence. These systems, however, need to be proved both technically and economically before being promoted on a large scale. Continuing research and development, as well as operational experience with systems in the field, should provide confidence in the ability of integrated systems to perform as expected.

SECTION 7.0

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

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